Superconducting Nb_3Sn-Cable R&D for Magnets for Future Hadron Colliders

Bauer, P., Fermilab
Ambrosio, G., Fermilab
Kerry, E., Fermilab
Ozelis, J., Fermilab
Andreev, N., Fermilab
Miller, G., NHMFL
Miller, J., NHMFL
Scanlan, R., Lawrence Berkeley National Laboratory
Higley, H., LBNL
Dietderich, D., LBNL
Ghosh, A.K., Brookhaven National Laboratory

In the R&D effort towards a post-LHC hadron collider, Fermilab, Lawrence Berkeley National Laboratory, and Brookhaven National Laboratory are developing a prototype for a 10 to 12 T block-type, common coil dipole magnet operating at 4.5 K using brittle Nb_3Sn superconductor with the "React & Wind" technology. An experimental program, using cables made from ITER type Nb_3Sn strand, was launched to investigate the degradation of the critical current due to bending (as for example in the coil ends) and pressure (as for example during magnet operation). A detailed description of the objectives and techniques used for the React & Wind cable R&D program is given in reference 1.[1]

Three prototype cables were fabricated from 0.7 mm, 0.5 mm and 0.3 mm diameter strands, all 15 mm wide. Samples of these cables were successfully characterized in two measurement campaigns at NHMFL in the course of the year 2000. The test facility at NHMFL consists of a 12 T split solenoid with a radial access port for the sample. The sample current is limited to about 13 kA by the current carrying capacity of the current leads into the test rig. A pressure piston acting through the bore of the split solenoid system applies transverse pressure on the sample in the range 0 to 300 MPa. The sample-holder contains two test cables spliced at the bottom and connected to the current leads on top. The portion of the current lead connecting to the sample holder has been re-designed by NHMFL to fit this particular sample holder. Voltage taps along the cable samples allow one to measure the voltage along the cable in the 150 mm high field region (where the sample crosses the solenoid bore). After cool-down to 4.2 K with liquid helium, the pressure piston is activated to produce a chosen pressure on the sample, the split solenoid is ramped to a chosen background field (range 8 to 11 T), and the current is gradually increased in the sample. The voltage over the sample is recorded to determine the critical current, i.e. the current at which the super-to-normal conducting transition occurs.

To measure the degradation of the critical current due to bending, one set of samples (of each cable type) was reacted on a spool and straightened after reaction during the sample-holder assembly, while another set was reacted in the straight shape (thus revealing no bending degradation). The effect of pressure on the critical current was obtained by varying the pressure in the transverse pressure system during the measurement run. First results of the React & Wind cable R&D program were published in reference 2.[2] In brief review the results are: (1) that the cable results are well correlated with separate measurements of cabling and bending degradation on single strands, (2) that the transverse pressure can be understood and predicted on the basis of a simple strain model, and (3) that the use of a stainless-steel core in the cables can cause increased bending degradation.

Acknowledgements: This work was supported by the U.S. Department of Energy.

---

[1] Ambrosio, G., *et al.,* "Study of the React and Wind Technique for a Nb_3Sn Common Coil Dipole," Proceedings of the 16th Magnet Technology Conference, Ponte Vedra Beach, Florida, Sept. 1999.

[2] Bauer, P., *et al.,* "Fabrication and Testing of Rutherford-type Cables for the React and Wind Accelerator Magnets," Proceedings of the Applied Superconductivity Conference, Virginia Beach, Sept. 2000.

Protection Heater Performance of a Superconducting Protection Switch

Dixon, I.R., NHMFL
Markiewicz, W.D., NHMFL

A CuNi persistent quench switch was manufactured and tested to characterize the electrical performance of the heaters. This switch is a non-inductively wound coil consisting of CuNi/NbTi triplet conductor and is designed to have a resistance of 7.2 Ω. The start and finish leads are at the inner diameter of the coil and the turn-around loop is at the outer diameter. The coil contains two types of stainless steel strip heaters. One heater type is a rolled down braid and the other is a fine mesh. The mesh heater is approximately six times more resistive than the braid heater, effectively reducing the required current needed to quench the switch.

The conductor strands are insulated with polyvinylformal and the triplet is additionally insulated with a glass fiber braid. Since the conductor insulation is doubled, additional cloth layers would only reduce the thermal conductivity. Therefore, as part of a development, half of the heaters were installed between cloth layers and the other half were installed without.

The coil was constructed with six heaters of each type. One heater of each type was placed between each layer of the 7 1/2 layer coil (no heaters between layers 7 and 8). The heaters were placed in four radial slots, with the mesh heaters at 120° and 240°, and the braid heaters at 180º and 300º, relative to a lead-in. The glass cloth layers occur between layers 1 and 2, layers 3 and 4, and layers 5 and 6.

With a background field of 1 T and a switch current of 300 A, the heaters in the switch were pulsed with an applied current for a duration of 1 s and the resulting voltage of the switch was recorded as a function of time. To compare the different heater configurations, plots of quench reaction time and heater current were made.

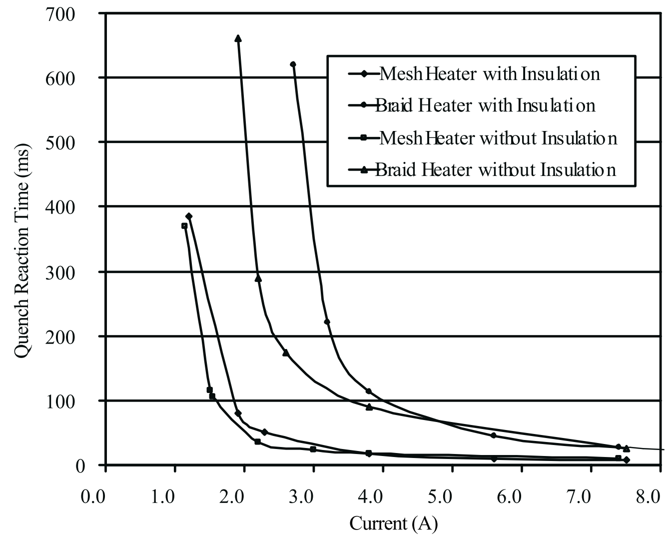

Figure 1. Current for switch quench initiation with heaters of various configuration, one heater.

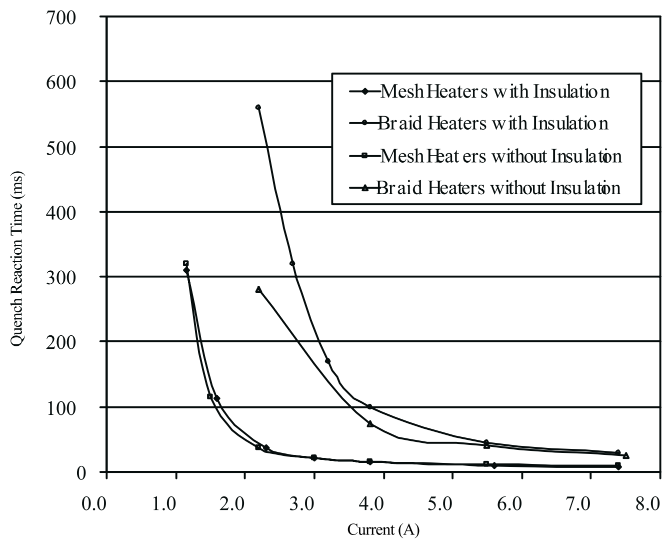

Figure 2. Current for switch quench initiation with heaters of various configuration, two heater.

Fig. 1 contains results for the case of one active quench heater. As expected, the current and time required to quench the switch is less for the mesh heater. A small insulating affect can be seen with the added insulation as well. Fig. 2 contains results for the case of two active quench heaters, where a similar pattern can be seen. Overall, the quench heaters and switch performed very well, where for any case as little as 4 A would quench the switch in 100 ms or less.

Apparent Interlaminar Shear Strength of Short Beam Epoxy-Glass Composites at 4.2 K

Dixon, I.R., NHMFL
Markiewicz, W.D., NHMFL
Toplosky, V., NHMFL
Walsh, R.P., NHMFL

Investigation of the influence on the interlaminar shear strength of epoxy-glass composites from the addition of a sizing agent is performed. The glass cloth of the composites represents the end flange cloth of Nb_3Sn coils which undergo a high temperature heat treatment and subsequent epoxy impregnation. There is a possibility to increase the strength of the cloth by adding an epoxy-compatible sizing to the area after heat treatment.

The influence of sizing on the cloth is quantified by conducting three-point bend tests on short beam composites. The test is an ASTM[1] standard test that is used to compute apparent interlaminar shear strength. The samples are nominally 6 mm x 6 mm x 42 mm making a length to thickness ratio of 7 with a span to thickness ratio of 5. The apparent interlaminar shear strength is computed by $\sigma = 0.75\ P_B/bd$, where P_B is the breaking load, and b and d are the width and thickness of the specimen respectively.

Four sample types representing Nb_3Sn coils were made. Two were heat treated in oxygen and two were reacted in argon atmospheres at 700 C for 2 hours. The samples heated in oxygen produced a white, cleaned product and the samples heated in argon had a black appearance due to carbon. Of these two types of samples, one of each had 2% Silane in an alcohol carrier applied to it. One additional sample type was made with a Volan type sizing, which was commercially applied. The sample configuration is listed in Tab. 1.

Sample ID	Cloth	Cloth Thickness	Sizing	Heat Treat	Epoxy
A	60 x 58 Plain Weave	0.0038"	Volan	None	NHMFL 61
B	58 x 55 Satin Weave	0.009"	Greige	1 hr @500° C Oxygen	NHMFL 61
C	58 x 55 Satin Weave	0.009"	2% Silane Alcohol	1 hr @500° C Oxygen	NHMFL 61
D	58 x 55 Satin Weave	0.009"	Greige	1 hr @500° C Argon	NHMFL 61
E	58 x 55 Satin Weave	0.009"	2% Silane Alcohol	1 hr @500° C Argon	NHMFL 61

Table 1. Epoxy-glass samples for interlaminar shear strength measurements.

Up to nine samples of each type were made, but only three of each were tested. Fig. 1 contains a plot of the strength with deviations. The results of each sample type grouped together very well. The lowest strength was the epoxy glass with Volan sizing. The inclusion of carbon in comparison to the oxygen heat treated samples does not appear to reduce the strength of the composites. The addition of sizing, however, is shown to have a slight but positive increase in the strength.

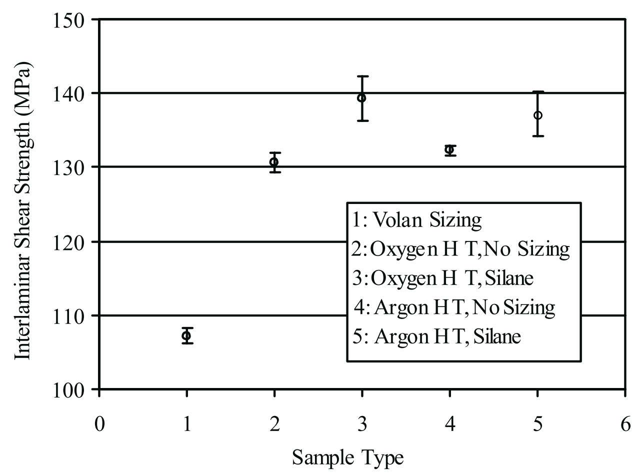

Figure 1. Apparent interlaminar shear strength results of epoxy-glass composites at 4.2 K.

[1] Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method, D2344-84, Annual Book of ASTM Standards, 1984.

MAGNET TECHNOLOGY

Magnetoresistance of Large Aluminum Coils

Goodrich, R.G., Louisiana State Univ., Physics and Astronomy

In the design of a maximum efficiency solenoid for space applications, several factors are involved in the choice of the wire material from which it is constructed. The current carrying material should be of low resistance at the temperature of operation to minimize joule heating, the coil resistance should not vary appreciably in the presence of the magnetic field produced by the coil, and because it is for space applications the material must have low mass. High purity aluminum is the material of choice because of three properties that make it optimal for magnet construction.

- At 77 K, unstrained, high purity aluminum has one of the lowest resistivities of any metal (ρ=0.254$\mu\Omega$-cm), thus reducing the power requirements for creating magnetic fields
- Aluminum is a low-density (2.6989 g/cc) material and the end product magnet will be of low total mass compared to similar designs involving copper or other elements
- The magnetoresistance of unstrained aluminum at low temperatures is lower than that of copper.

In order to check the magnetoresistance of a coil after it was wound and potted, measurements of the magnetoresistance were made to 10 T in the 195 mm bore resistive magnetic at 300, 90 and 60 K. The coil consists of a 6-inch diameter by 12-inch long closely wound solenoid, wound from 99.999% aluminum in four layers capable of producing 2 T for time periods less than one second without excessive heating. This coil will be used at 77 K in a plasma confinement system at Marshall Space Flight Center, AL. Since strain can change the electrical properties of Al, the completed coil parameters needed to be determined. A small increase in the positive magnetoresistance was measured as the temperature was lowered, but not sufficient to prevent the use of the coil for the intended application.

Further testing of the completed coil needs to be done by energizing the coil to its full field for the required times, and measurements of the resistivity, inductance, and strain induced by the operation need to be done. Plans to make these measurements at the NHMFL, Los Alamos are in progress.

Data Analysis for the CICC Model Coil of the Indian Institute for Plasma Research

Prestemon, S., NHMFL
Sayre, S., FSU, Computer Science and Engineering
Luongo, C., NHMFL/FAMU-FSU College of Engineering
Miller, J., NHMFL

This was a collaborative research effort between the NHMFL and the Indian Institute for Plasma Research (IPR). The scope of the effort was to utilize the NHMFL's magnet design tools and expertise to analyze experimental data obtained by the IPR on a model coil relevant to the design of SST-1, India's experimental fusion device. The model coil was wound with essentially the same full-scale conductor to be used in SST-1, a nominal 10 kA cable-in-conduit conductor (CICC) made of NbTi strands for operation at 5 T and 4.5 K (supercritical helium). The model coil consisted of 8 double pancakes with the following approximate dimensions: 36 cm inner diameter, 72 cm outer diameter, and 28cm height. To simulate the actual conditions that will be experienced by the conductor in the fusion device, the model coil was placed inside a 4-coil toroid producing a longitudinal pulsed field, while a pair of central bucking solenoids placed on the model coil's inner bore were used to generate a pulsed transverse field (see Fig. 1).

The NHMFL was given information on the test setup and procedures, as well as a voluminous amount of data corresponding to the entire experimental campaign. NHMFL's scope of work consisted of: (a) Creation of a hydraulic model, (b) Creation of a magnetic model, (c) Data reduction and interpretation, (d) Computer simulation of quench and comparison with experiment, and (e) Conclusions and recommendations.

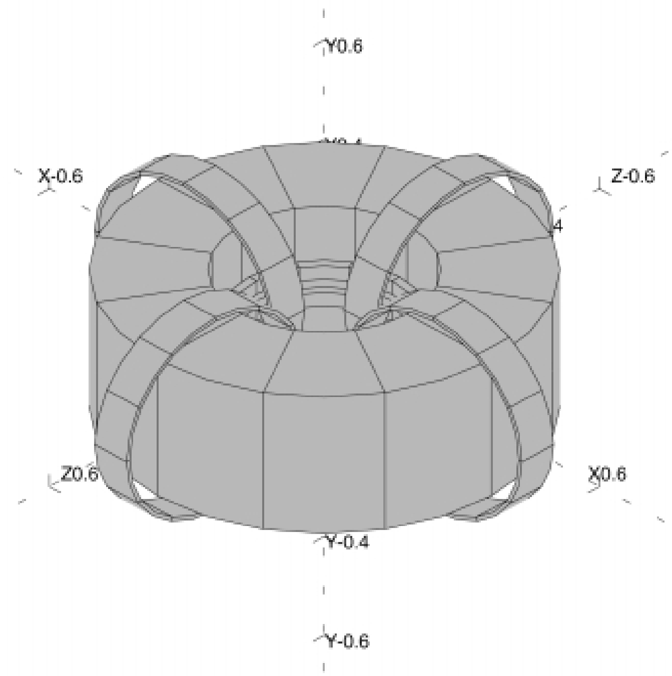

Figure 1. Configuration of the model coil inside four toroidal pulsed coils.

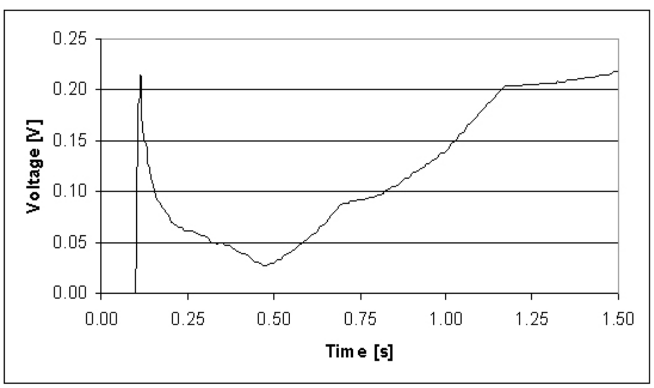

Figure 2. Normal zone voltage in the model coil.

The first step was to create a hydraulic model of the CICC test coil to be used in the quench simulations. The quench was numerically simulated using the computer code Gandalf.[1] Quench was initiated by pulsing the external poloidal and toroidal coils, the quench triggering mechanism being AC losses in the conductor. An AC loss model was established using standard expressions for both transverse and longitudinal pulses. The parameters in these models were adjusted to match the observed quench initiation threshold. This was an indirect (but rather accurate) way of determining the AC loss time constant for the conductor. The time constant for transverse pulses was within the expected range, however, the longitudinal time constant (corresponding to the toroidal field pulses) was significantly higher than expected. This was also consistent with the experiment that showed the poloidal pulsed coils alone were not able to initiate a quench, while the four toroidal coils (longitudinal pulse) could, by themselves, quench the sample. The numerical simulations cannot, by themselves, explain this higher-than-expected longitudinal AC loss.

After matching the observed quench initiation behavior, the quench evolution was analyzed without further adjustments to the model. The simulations uncovered a very complex scenario for quench evolution, with multiple zones being formed near the pressure relief ports, with subsequent coalescence, and growth. The integrated effect of this normal zone growth is captured in Fig. 2, showing the total voltage along the sample. A more complete account of the simulation results was presented at the Workshop on Computation of Thermo-Hydraulic Transients in Superconductors (Frascati, September 2000), with the technical report to be published in *Cryogenics*.

A number of valuable lessons were learned from the IPR model coil data analysis. First, the experimental data, together with the numerical simulations, strongly indicate that parallel AC losses are significantly higher than would traditionally be anticipated, and point to a concern that must be addressed in future designs in cases where a significant length of conductor is exposed to pulsating longitudinal fields. Second, despite the complex disturbance scenarios, the simulation code (Gandalf) was capable of capturing the highly dynamic quench propagation. Unfortunately, the experiment had not been designed or instrumented to capture this fine detail so that confirmation of code performance is not possible.

---

[1] Bottura, L., Cryogenics, **32** (7), 659 (1992).

HTS Insert Coil Development

Weijers, H.W., NHMFL
Schwartz, J., NHMFL/FAMU-FSU College of Engineering

This report describes research towards high temperature superconductor (HTS) insert coils in three areas. First, we describe the testing of small coils and then short samples in high magnetic fields, then the design process of a 5 T insert magnet.

Several double pancake coils of reacted Bi-2223 conductor were wound and tested at 4.2 K in magnetic fields of to 19 T. The winding thickness was about 1 mm to ensure homogeneity of stress and strain. The Lorentz-force induced strain was measured while increasing the operating current until large plastic yield and critical current degradation occurred. The strain at failure was compared to the strain limit of the conductor under uni-axial tension to study the effect of conductor plasticity and bending. Additionally, single pancakes of Bi-2223 conductor reinforced with stainless steel strips were tested at 4.2 K up to about 300 MPa Lorentz-force induced stress. No irreversible degradation was observed for this conductor. Both its strength and critical current density make this an interesting candidate conductor for application in high field insert magnets.

Critical currents in both Bi-2212 and Bi-2223 conductors were measured in applied fields up to 33 T. Samples originated at Oxford Superconducting Technologies (OST) and American Superconductor Corp., respectively. Both are potential conductors for insert magnets. Modifications to the sample holder were implemented and resulted in significant reductions of the signal/noise ratio and minimum required ramp rates for the sample current. The commonly used criterion of 1 microvolt/centimeter can now be applied to interpret the data. Tape samples were tested with the applied field both parallel and perpendicular to the flat surface. With engineering current densities between 200 and 300 A/mm^2 at 4.2 K, 25 T parallel field, these samples exceed the minimum current density requirements for typical insert magnets.

As a prototype for a 5 T inner section of a 25 T superconducting research magnet, we have started designing an insert magnet with a free bore of 40 mm, 160 mm outer diameter, 180 mm height, and an average current density of around 90 A/mm^2. The entire project is in collaboration with OST, who supplies the Bi-2212 conductor, among other contributions. The concept is a 3-section system, consisting of a double pancake wind-and-react inner section, a react-and-wind double pancake middle section, and a layer wound outer section. The intention is for each section to be strain limited, using reinforcement in the two outer sections. The optimum crossover diameters between sections depends on the critical current density, insulation, winding thickness, and effects of bending strain and reinforcement. An initial design has been developed. Testing of prototype double pancakes in high magnetic fields will help to determine the final optimized radial dimensions of the three sections.

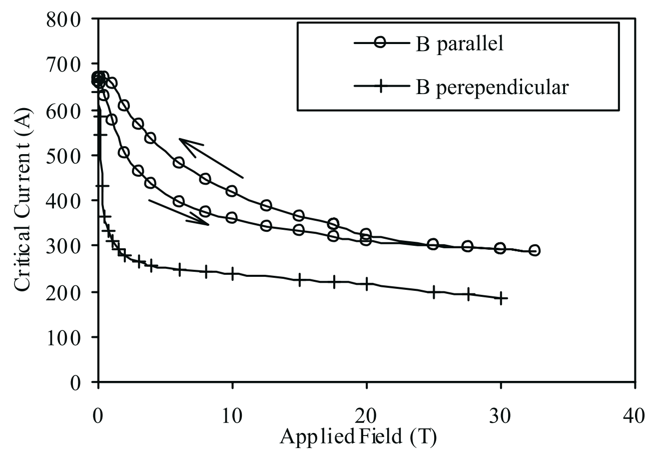

Figure 1. Field dependence of the critical current of a Bi-2223 sample of 0.9 mm^2 cross section.